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Evaluation of Enewetak
Radioactivity Containment

National Research Council, Washington, DC

Prepared for

Defence Nuclear Agency, Washington, DC

Mar 82

U.S. Department of Commerce
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For information regarding this document, write the Executive Director, Advisory Board on the Built Environment, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

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EVALUATION OF
ENEWETAK RADIOACTIVITY CONTAINMENT

Committee on Evaluation of Enewetak
Radioactivity Containment
Advisory Board on the Built Environment
Commission on Sociotechnical Systems
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Between 1948 and 1958 the Enewetak Atoll in the Marshall Islands was the site of 43 nuclear explosions, part of the government's nuclear testing program. Responding to the demands of the Enewetak people, the government in 1972 decided to rehabilitate the atoll. In the cleanup process, radiologically contaminated soil and debris from many of the atoll's islands were placed in a massive, domed concrete containment structure built over one of the bomb craters on Runit Island. In order to provide the people of Enewetak and the Marshallese Government with an objective assessment of the containment structure's safety, the Defense Nuclear Agency asked the Advisory Board on the Built Environment of the National Research Council to study the matter. The committee appointed to conduct the study concentrated on two issues: (1) the potential hazard of transuranics being transported to the surrounding environment from the structure, and (2) the possible sequence of events that would affect the structure's physical integrity and the radioactive hazards that would result from breachment of the dome. The committee's report concludes that the containment structure presents no health hazard to the Enewetak people now or in the future. The committee went on to recommend periodic inspection of the dome. Runit Island, on which the dome is situated, was found to be unsafe due to highly toxic plutonium particles in the soil and was placed off-limits forever. In addition, the committee examined the possible radiation hazard on nearby Enjebi Island, a potential resettlement site.

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PREFACE

Between 1948 and 1958 Enewetak Atoll in the Marshall Islands was used for U.S. nuclear weapons testing and 43 devices were exploded there. In 1972 the federal government announced that it would rehabilitate the atoll and return it to the government of the Trust Territory of the Pacific Islands and, subsequently, to the Enewetak people, who had been moved to Ujelang in 1947, 125 miles southwest of Enewetak.

The Enewetak rehabilitation effort involved many departments of the federal government with the Defense Nuclear Agency (DNA) being charged with the major radiological cleanup responsibility. In the process of this cleanup, radiologically contaminated soil and debris from many of the islands in the atoll were collected and transported to Runit Island on the eastern side of the atoll. The contaminated material then was contained in a soil-cement matrix in Cactus Crater, which had been formed by one of the nuclear detonations. This material was surrounded by a concrete key-wall and covered by a concrete cap.

In order to provide the people of Enewetak and the Marshallese government with an objective assessment of the safety of this containment structure, the DNA requested the National Academy of Sciences, through the Advisory Board on the Built Environment* (ABBE) of the National Research Council, to "assess the effectiveness of the Cactus Crater structure in preventing harmful amounts of radioactivity from becoming available for internal or external human exposure"; the DNA added later that this assessment should be "set against an understanding of the expected living patterns of the people of Enewetak in terms of their degree of contact with Runit Island and their exposure otherwise to residual radioactivity on the atoll."

The committee appointed to conduct the study concentrated primarily on two issues: (1) the potential hazard of transuranics being transported to the surrounding environment from the structure in its present configuration, and (2) possible sequences of events that could affect the structure's physical integrity and an estimation of radioactive hazards that might result from the dome's breachment. Two subsidiary issues also concerned the committee and are commented on in the report; namely, possible hazards associated with the quarantined island of

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*Formerly the Building Research Advisory Board (BRAB).

Runit where the dome is located, and possible hazards from fission products that may arise if the northern island of Enjebi is resettled. Although this committee's charge was not expressly directed toward hazards associated with the resettlement of Enjebi, it must be emphasized that the risks from the consumption of food grown in the northern islands are high compared with any conceivable risk arising from rupture of the dome.

The reader of this report will discover that the committee depended heavily on information furnished by government agencies and their contractors. Insofar as possible it attempted to assess the quality of these data and, in one important instance (the drilling program described in the report), supervised the acquisition of new information about the quality of the dome's construction and the concentrations of radioactivity contained within it. In its interpretation of potential hazards associated with the dome the committee depended heavily on data acquired by groups at the Lawrence Livermore Laboratories led by V. E. Noshkin and W. L. Robison. Members of the committee reviewed the sampling and analysis procedures used by these groups. In addition, all the work on the Enewetak operation done by these groups has been subjected to critical review by a select panel of experts from other government laboratories and from universities; much of the work also is published in scientific journals and, thus, has been subjected to peer review there. The Committee therefore is satisfied that the information it has received concerning environmental sampling, analysis, and dose assessment is of high quality.

The Committee on Evaluation of Enewetak Radioactivity Containment wishes to acknowledge the cooperation of the many individuals who provided extensive information and assistance. The committee is particularly grateful to Thomas Jeffers, Director for Logistics and Administration, Defense Nuclear Agency, Alexandria, Virginia; Roger Ray, Deputy for Pacific Operation, Nevada Operations Office, Department of Energy, Las Vegas; Bryon L. Ristvet, Test Directorate, Field Command, DNA, Kirtland Air Force Base, New Mexico; William Robison, Section Leader, Terrestrial and Atmospheric Sciences, Environment Sciences Division, Lawrence Livermore Laboratory, Livermore, California; Victor Noshkin, Marine Sciences, Environmental Sciences Division, Lawrence Livermore Laboratory, Livermore, California; and David Stark, Concrete Materials Research Department, Portland Cement Association, Skokie, Illinois.

Robert W. Morse
Chairman

Chapter 1
SUMMARY AND CONCLUSIONS

In conducting its assessment of the effectiveness of the Cactus Crater structure in preventing harmful amounts of radioactivity from becoming available for internal or external human exposure, the Committee on Evaluation of Enewetak Radioactivity Containment organized a drilling program to obtain cores through the entire depth of the finished containment structure, visited Enewetak Atoll to examine the structure and observe the drilling operation, reviewed all relevant data and reports connected with the cleanup program, and interviewed key individuals associated with the program, including those responsible for radiation measurements and their interpretation. During its deliberations, the committee focused on such issues as the nature of the radioactive materials contained within the structure, the possible changes that might occur to the structure as time passes, the ways in which radioactive material now contained in the structure conceivably might be transported elsewhere, and the radioactive risks to which the people of Enewetak would be exposed in the most extreme of these hypothetical cases.

1.1 The Containment Structure

The committee believes that the Cactus Crater containment structure and its contents present no credible health hazard to the people of Enewetak, either now or in the future.

The function of the containment structure, as the committee perceives it, is to prevent hazardous human exposure to the radioactive material buried within it, and the committee believes it is highly unlikely that any sequence of events would prevent the structure from performing this function. Any flushing or spilling of the contents of the structure into the lagoon or ocean that might occur as a result of cracking, settlement, or storm damage will not create an unacceptable radioactive hazard. Indeed, even if the entire radioactive contents of the containment structure were to find its way into the lagoon, no unacceptable hazard would result.

Although no significant radioactive hazard would be created if the containment structure were to fail in any way, it is prudent to maintain the physical integrity of the structure in order that it may continue to prevent direct human access to the radioactive material it contains. Thus, inspection of the dome should take place periodically and after severe storms. Cracking or settling of the panels should not be of concern, but breaches in the riprap should be repaired to provide protection against wave action during storms.

1.2 Related Issues

The committee was asked that its assessment of the Cactus Crater structure be "set against an understanding of the expected living patterns of the people of Enewetak in terms of their degree of contact with Runit Island and their exposure otherwise to residual radioactivity on the atoll." In this regard the committee makes two comments.

1.2.1 Runit Island

There is a hazard of uncertain magnitude on Runit Island because of the possible presence of plutonium not located and removed during the cleanup (a situation unique to Runit), and, for this reason, Runit has been made off-limits, a status the committee does not dispute. It is likely, however, that the people of Enewetak and others believe Runit to be off-limits because of hazards associated with the containment structure. The committee therefore emphasizes that its conclusion regarding the safety of the structure should not be interpreted to mean that Runit is thought to be harmless. It may well be that an important future function of the containment structure will be to serve as a reminder to everyone that the island is to be avoided in view of the possible presence of plutonium there.

1.2.2 Enjebi Island

It is likely that the Dri-Enjebi sooner or later will resettle their home islands in the northern part of the atoll. Radiation exposures associated with such a move far exceed any exposures that can be associated with the dome or with the radioactivity remaining in the lagoon. Indeed, for people who might live on Enjebi in the near future, radiation exposures due to strontium-90 or cesium-137 in locally grown foods may become excessive in relation to current U.S. standards for a general population, especially if food is not imported from other islands of the atoll or from outside.

Chapter 2
BACKGROUND

2.1 Nature of the Islands

The Marshall Islands, which comprise the eastern part of Micronesia, are about halfway between Hawaii and the Philippines. The Marshalls consist of 29 coral atolls and 5 coral islands having a total land area of only 70 square miles (Figure 1). Each atoll consists of many separate islands connected by coral reefs that usually form an enclosure around a central lagoon.

The temperature in the Marshalls averages about 80°F with little seasonal variation. The northern islands receive about 60 inches of rain annually and the southern islands, about three times that amount, but moisture rapidly drains out of the soil and the islands are relatively arid. The amount of rainfall also varies considerably from year to year in the northern islands and droughts are common. Food crops consist of coconut, pandanus, arrowroot, and bread fruit. Famine conditions are not infrequent because of drought even though the reefs and lagoons provide a stable source of marine food (Tobin 1967).

2.2 Normal Economy

Prior to World War II, the economy of the Marshalls was based on subsistence crops and fishing, supplemented by the export of copra (the dried meat of the coconut). This continues to be the case today on most of the islands; however, government activities at Majuro and at the missile range on Kwajalein are now major sources of employment and, hence, of income for the people in the Marshalls.

In 1977, the total population of the islands was estimated at about 25,000. Of these, 8,000 were at Majuro and 5,000 on Ebye Island at Kwajalein. A portion of the money earned by Marshallese employed at these two centers filters back to the subsistence-based islands. Presumably, the economy at Enewetak after resettlement will be based on subsistence crops and fishing, incomes from relatives employed at Majuro and Kwajalein, export crops (initially nonexistent), and U.S. support programs insofar as they continue to exist after independence.

2.3 Enewetak Atoll

Enewetak is a typical atoll (Figure 2); 40 islands surround an elliptical lagoon 23 miles long and 17 miles wide. The total land area is only 2.26 square miles.

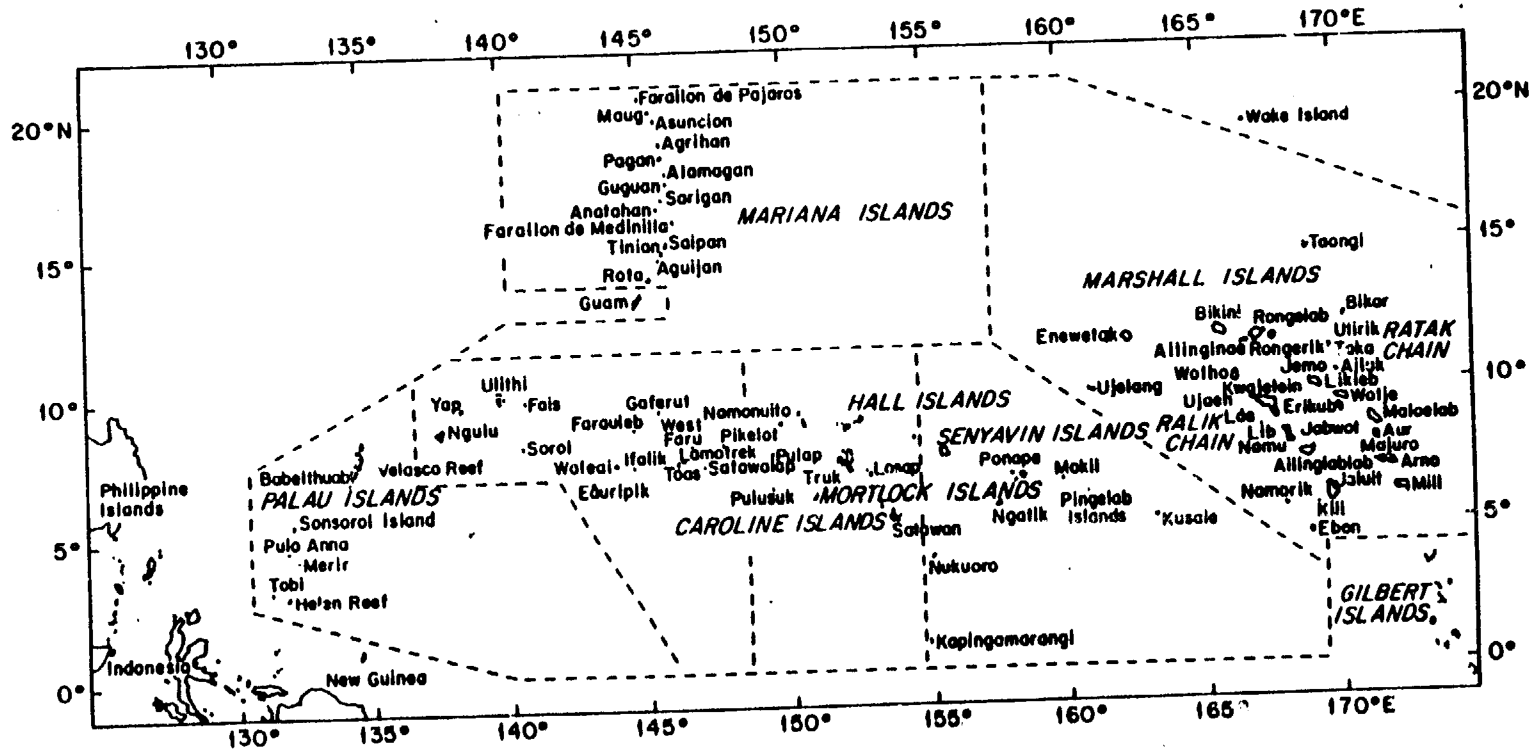

FIGURE 1 The U.S. Trust Territory of the Pacific Islands.

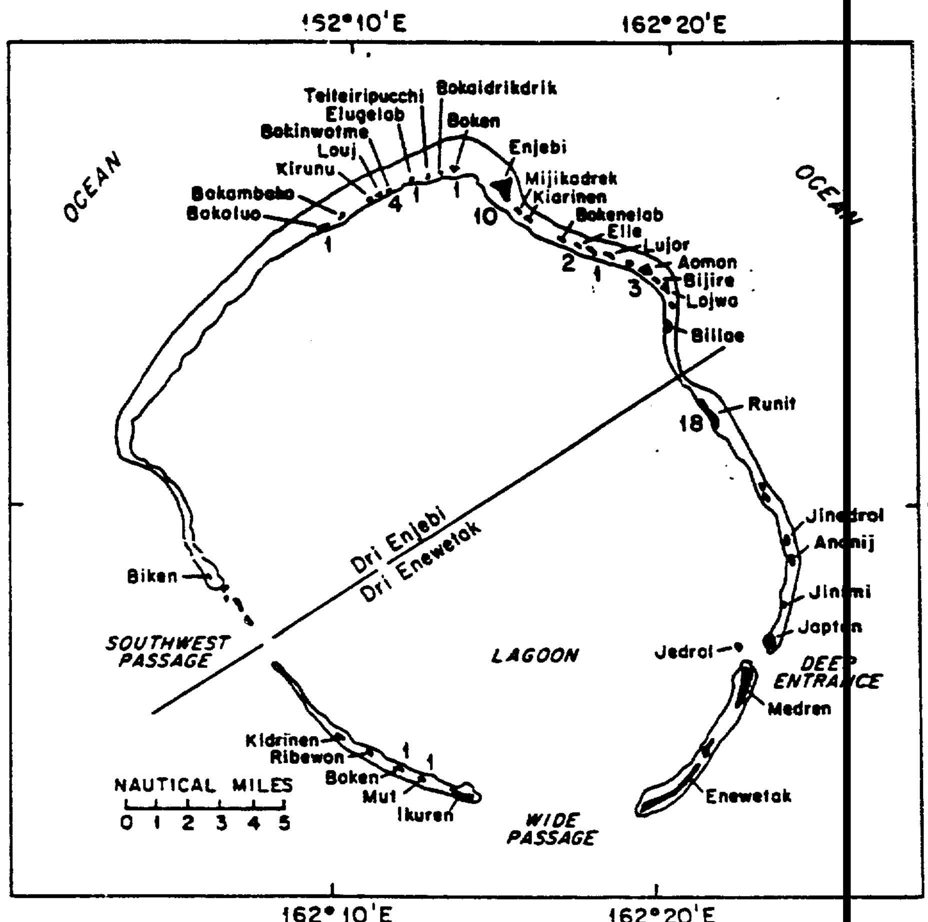

FIGURE 2 Map of Enewetak Atoll. Numbers indicate the number of nuclear tests conducted.

Although the Marshall Islands were discovered by the Spanish in 1529, they remained in practical isolation for over two centuries. Germany claimed the islands in the latter part of the nineteenth century and developed copra trading activities. Enewetak, with the rest of German possessions in Micronesia, was seized in 1914 by the Japanese who continued the copra trade. Between 1939 and 1941 Enewetak was developed as a military base by the Japanese, and the local men were pressed into service as laborers. In February 1944 U.S. military forces assaulted Enewetak. Possession was won only after the death of 3,200 Japanese, 350 Americans, and 17 of the local people (Kiste 1975, Morison 1961). Following the battle, the United States established a large base on the atoll, and after the Pacific war the United States was granted a trusteeship over the islands by the United Nations (UN). In 1947 President Truman notified the UN that Enewetak was to be used as a nuclear weapons proving ground and the inhabitants were removed to Ujelang, 125 miles to the southwest.

2.4 The Enewetak People

There are two political-social subdivisions within the Enewetak people--the Dri-Enjebi, who occupied the northern islands, and the Dri-Enewetak, who lived on the southern islands. Although these two tribes had different chiefs and social organizations, they lived together peacefully and with extensive intermarriage for many generations. Both groups also now include people descended from intermarriages with the people of Ujelang.

After the battle of Enewetak in February 1944 the people were housed on Aomon (Figure 2) where they were supported by the U.S. Navy until 1946 when they were moved temporarily to Kwajalein. They then were returned to Aomon for about a year and, in 1947, 142 of them were moved to Ujelang, a much smaller atoll (only 0.6 square miles of land area). In April 1980 approximately 500 of the people returned to Enewetak and now are living on the southern islands of Enewetak, Medren, and Japtan where housing has been constructed for them by the U.S. government (Figure 3).

The experience of the Enewetak people on Ujelang has been documented by Tobin (1967). The original Ujelang people had migrated to Jaluit in the 1880s and some later migrated to Enewetak. Although times often have been difficult on the smaller atoll, the transition to Ujelang was aided by these historical ties and the fact that it was uninhabited. The dual social structure of Dri-Enewetaks and Dri-Enjebis was maintained throughout the entire 33-year period on Ujelang and exists today. At the present time, however, both groups reside only on the southern islands, the lands of the Dri-Enewetaks. Given the very powerful cultural importance attached to land in the Marshalls, as well as its economic value, the Dri-Enjebi, not surprisingly, wish to resettle their home islands.

2.5 Weapons Testing

Between 1948 and 1958, 43 nuclear weapons were exploded on Enewetak Atoll. Some were sufficiently powerful to obliterate whole islands or blow considerable portions of islands into the lagoon or the ocean. Many craters can be seen from the air as deep blue patches in the surrounding sea or as water-filled pools on the islands. The coral

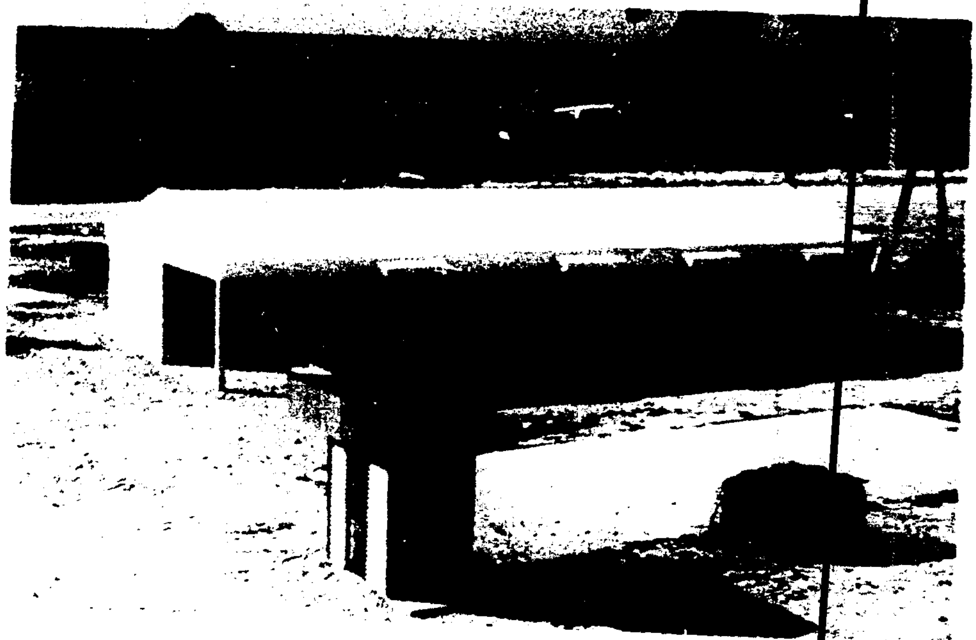

FIGURE 3 One of a variety of one- and two-story resettlement house styles.
(Photo courtesy of B. L. Ristvet)

of the reef and of the islands is freely permeable to ocean water; therefore, the craters are an effective connection with the lagoon and the ocean even if they are located within an island.

Most of the testing was done on the northern part of the atoll. (See Figure 2 for the number and location of the tests.) The test personnel were based in the southern area, and Enewetak Island, the largest in the atoll, accommodated many buildings and an airstrip capable of handling the largest aircraft.

2.6 References

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Morison, Samuel Eliot, History of United States Naval Operations in World War Two, vol. 7, pp. 283-304, Little Brown and Company, Boston, 1961.

Tobin, Jack A., The Resettlement of the Enewetak People: A Study of a Displaced Community in the Marshall Islands, Ph.D. dissertation, University of California, Berkeley, 1967. (Available from University Microfilms, Inc., Ann Arbor, Michigan.)

Chapter 3
THE CLEANUP

3.1 Cleanup Proposals

In 1972 the U.S. government announced that it would return the Enewetak Atoll to the government of the Trust Territory of the Pacific Islands and, subsequently, to the people of Enewetak, and an effort to clean up and rehabilitate the atoll was initiated. Planning extended from 1972 to 1977, and the people of Enewetak were involved in the major decisions. The cleanup operation itself extended from May 1977 to April 1980. A detailed on-site radiological investigation by the Atomic Energy Commission (AEC), cleanup by the Department of Defense (DOD), and rehabilitation (homebuilding and crop planting) by the Department of the Interior (DOI) were carried out to some extent concurrently. The planning and cleanup operations are described in detail in a lengthy DNA report (1981) and are summarized in a DNA fact sheet (1980).

3.2 Cleanup Criteria

The environmental impact statement (EIS) for the cleanup, resettlement, and rehabilitation of Enewetak Atoll (Defense Nuclear Agency 1975) established a series of standards to be met. Radiation doses to the returning population were not to exceed 0.25 rem per year to the whole body and marrow, 0.75 rem per year to the thyroid, 0.75 rem per year to bone, and 4 rem over a period of 30 years to the gonads. These "guides for cleanup planning" were followed in the EIS summary by the statement:

> Cleanup of soil containing plutonium can be handled on a case-by-case basis using the following: (a) less than 40 pCi/g of soil--corrective action not required, (b) 40 to 400 pCi/g of soil--corrective action determined on a case-by-case basis considering all radiological conditions, (c) more than 400 pCi/g of soil--corrective action required.

It was recommended that only islands satisfying criterion (a) should be used for residence and subsistence agriculture. Islands satisfying criterion (b) could be used for agriculture (e.g., coconut trees for copra production) and those satisfying criterion (c) could be visited for food gathering (e.g., fishing and gathering birds' eggs).

These standards subsequently were modified by the Department of Energy (DOE) to include all the transuranics, not just plutonium. The land-use cleanup standards also were revised to permit not more than 40 pCi/g for residential islands, 80 pCi/g for agricultural islands, and 160 pCi/g for food-gathering islands.

3.3 Disposal Options

During the planning stages a major consideration was the method of disposal for any plutonium-contaminated material. Several options were initially considered "including returning it to the United States, casting it into concrete blocks, dumping it into a crater with a concrete cap, or dumping it in the ocean or lagoon" (Defense Nuclear Agency 1981, p. 94). Although strong arguments were made for lagoon or ocean dumping, the Environmental Protection Agency (EPA) believed that national policy prohibited such disposal. This view prevailed over that of the Energy Research and Development Administration (ERDA) and the final environmental impact statement (April 1975) identified crater entombment as the selected disposal method. Disposal criteria were reviewed again in August 1977 by the so-called Bair Committee. This group advocated ocean dumping as the preferred solution with lagoon dumping as an acceptable alternative but recognized that any change would require the EIS to be reopened and that EPA opposition to those alternatives would still remain. The Bair Committee's final view was that "terrestial disposal on Runit Island with a concrete cover" was the best practical alternative (letter from W. J. Bair, et al. to J. L. Liverman, Assistant Administrator for Environment and Safety, ERDA, August 17, 1977). Thus, the cleanup plan finally adopted called for radiologically contaminated soil and debris present on many islands in the atoll to be collected and transported to Runit and contained in a soil-cement matrix in Cactus Crater, surrounded by a concrete key-wall, and covered by a concrete cap.

3.4 Radioactive Contaminants

The radionuclides of principal concern at Enewetak are the transuranics, mainly plutonium-239, and the fission products, strontium-90 and cesium-137. The transuranics are relatively insoluble and therefore have remained very near the surface. The strontium and cesium, however, are more soluble and have leached to a considerable depth. Indeed, the DNA (1980) stated:

> The AEC's radiological survey had disclosed that, except on the island of Runit, most high transuranic concentrations were in the top few centimetres of soil. This was not the case with suburanics which, because of their water solubility, were distributed to considerable depth. . . . Excision of soil contaminated with suburanics [fission products], however, was simply not practicable. To do so would require such extensive soil removal as to render the island useless for habitation or subsistence agriculture.

Thus, the subsequent cleanup concentrated on the problem of transuranics.

The emphasis on transuranics in the cleanup operation also was influenced by the fact that Pu-239 has a half-life of 24,000 years whereas Sr-90 and Cs-137 have half-lives of about 30 years. In the near future, however, the fission products must be of great concern because of their rapid rate of movement through the soil and their very active incorporation into the food chain.

Since there was virtually no contamination on the southern islands, it was planned that only these islands would be settled at the beginning. Occupation of the northern islands after cleanup was to be postponed until radioactive decay brought the concentrations of Sr-90 and Cs-137 to acceptable levels.

3.5 Location of the Contamination

Before work could begin it was necessary to find out which islands were significantly contaminated and to identify the specific places where remedial work would be required. As has been explained, the cleanup was concerned with the transuranics, mainly plutonium, but plutonium emits only an alpha particle accompanied by a very low-energy x-ray so it is not practicable to measure it in the field. However, the plutonium is associated with americium, which has a sufficiently penetrating gamma ray for detection through several inches of soil. Aerial surveys and in-situ monitoring detected the significantly contaminated islands and specially designed detection equipment mounted on a tracked vehicle then was used for a detailed survey. Readings were taken at every intersection of a 50-meter grid. Soil samples at various depths were taken at each intersection for laboratory analysis to determine the plutonium/americium ratio. In areas of high contamination, samples were taken at 25-, 12.5-, and 6.25-meter intervals. This work provided the basis for radiation contour maps that would be used by the cleanup crews.

3.6 Nature of the Problem

The cleanup problem was not confined to surface soil contaminated with transuranics. During the weapons testing program, debris from tests frequently was cleared from a site and dumped in an old crater in preparation for reuse of the site for additional tests. All detectable dumps, crypts, and burial sites were excavated and any radioactive contents transferred to the Cactus Crater. Old blockhouses, sunken barges, and landing craft in less than 15 feet of water and other miscellaneous debris were collected, monitored, and disposed of in the containment structure, if contaminated, or in deep parts of the lagoon if not contaminated.

Retrieval from dumps often was difficult and a crypt on Aomon Island was so extensive that a year was required to plan and complete its excavation. About 16,000 items from World War II (unexploded artillery and mortar shells, hand grenades, small arms, and ammunition) also were detected, dug up, and detonated or removed by Navy Explosive Ordnance Disposal Teams. After the rubbish was removed, the top 6 inches of soil was scraped off, loaded into barges, and transported to Runit Island.

3.7 Safety of Operators

Despite the nature of the work, no significant radioactive contamination of the personnel is reported to have occurred. People working in situations where airborne hazards could be anticipated wore face masks and good personal hygiene procedures were required. The operators wore dosimeters. Routine urine analyses and film-badge readings showed no significant exposure. It should be noted that of over 5,000 filters from air samplers, over 50 percent showed no contamination from transuranic elements, over 95 percent showed less than 1 percent of the maximum permissible concentration (MPC), and none showed more than 10 percent of the MPC (Defense Nuclear Agency 1980). Over 4,000 U.S. servicemen served on the atoll during the cleanup and 6 lost their lives (2 deaths resulted from industrial accidents, 2 from a recreational accident, and 2 from causes "unrelated to the environment").

3.8 Cactus Crater

The Cactus Crater, which received all the contaminated debris and soil from the atoll, is situated on the reef side of the northern end of Runit Island (Figure 4). Most of the crater rim is on land, but before construction of the dome, about a quarter of the circumference was open to the ocean at high tide and another consisted of a narrow spit of coral. A surface shot in May 1958 produced the 350-foot-wide and 30-foot-deep crater. About 200 feet to the northeast of Cactus Crater on the ocean side is a somewhat larger crater, LaCrosse, which was produced by a surface shot in May 1956. The rim of LaCrosse at high tide appears only as a few isolated rocks above the water. The original plan was to use LaCrosse Crater first and to use Cactus only if there was more material than LaCrosse could hold. For logistical reasons, however, the order was reversed and Cactus alone proved to be sufficient size for the disposal operation.

The Cactus Crater was not formed in undisturbed rock. The Zebra Tower shot was detonated 217 feet southeast of Cactus in May 1948 and the Dog Tower shot, 291 feet southeast of Cactus in April 1951. These two shots caused fracturing of the rock around the site of Cactus (Defense Nuclear Agency 1981, p. 409). The Zebra Crater was filled in and oiled to prevent dust while the Dog Tower was being worked on, and the Dog Crater and contaminated areas were made "radiologically safe" by dumping the contaminated debris in the crater and then covering the contaminated area with clean sand. It is apparent, therefore, that there is a good deal of buried radioactive material near, but not inside, the Cactus Crater and that the surrounding rock is heavily fissured.

When the Cactus device exploded, a large amount of rock, much of it pulverized into small particles, was thrown upwards. Much of this material fell back into the crater so that the original hole was half filled with debris. The true crater is therefore twice as deep as it appears to be, and this was demonstrated several years ago when a hole was drilled through the debris to a depth beyond the bottom of the true crater. A gamma counter was lowered down the hole and activity levels were recorded at different depths (Figure 5). At the bottom of the visible crater, the counting rate increased sharply from near zero to about 4800 counts per second (cps). The counting rate then decreased

FIGURE 4 Runit Island before construction of the containment structure. (Photo courtesy of Defense Nuclear Agency.)

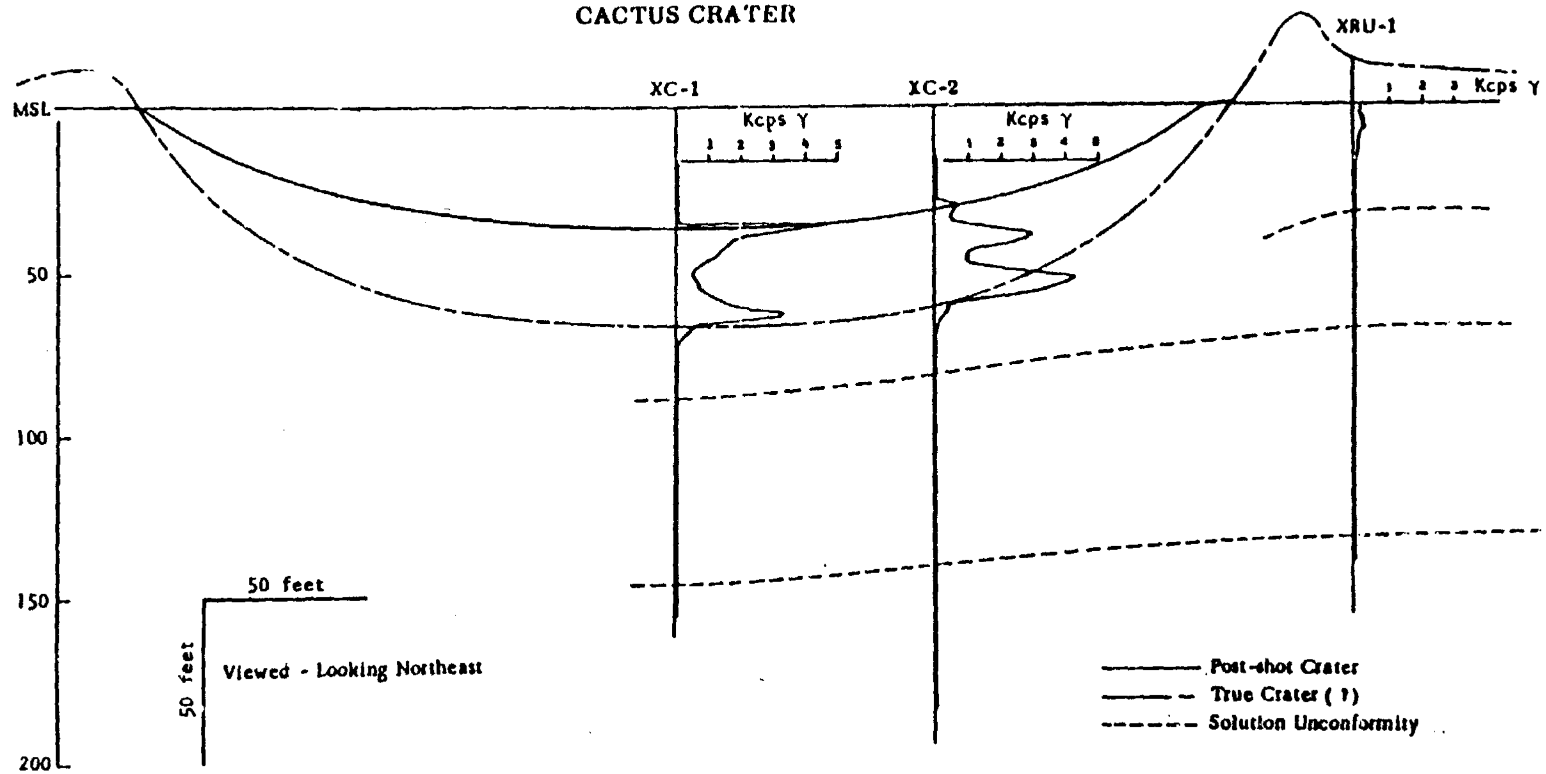

FIGURE 5. Well logs of gamma radiation (expressed as K cps) from drill holes XC-1 and XC-2 beneath Cactus Crater (Ristvet 1980). The true crater may be defined by points where increased activities occur beneath the fallback material in the crater.

to about 400 cps as the counter descended through the fall-back zone and rose again to about 3400 cps at the true bottom of the crater. The high count at the surface of the fall-back zone is probably due to the fact that small particles, which absorb more activity per unit of weight than large particles, fell back more slowly.

The high permeability of the coral rock ensures that the radioactive material within the fall-back zone has been continuously leached by sea water since 1958. Nevertheless, substantial quantities of radioactive material were present beneath the apparent bottom of the crater before any of the soil and debris from the islands was placed into it.

It is also possible that a part of Cactus Crater was formed out of a man-made extension of the island on the lagoon side of the reef (Defense Nuclear Agency 1981, p. 409); at least there is no appreciable beachrock present on the lagoon side of the crater.

3.9 Filling of the Crater

The contaminated soil was transported by barge to Runit Island, where it was mixed with cement and attapulgite to form a mixture designed for use in the tremie method of underwater concrete placement. Using this method, water is added to the cement-soil mixture to form a slurry that is pumped through a pipe to the underwater location; the end of the pipe is kept below the surface of the ejected slurry to prevent segregation of the cement and soil.

The crater was filled to the low-tide water level using the tremie method. The key-wall then was sunk to a depth of 1 foot where the beachrock was solid and to a depth of 8 feet where the beachrock was fractured or absent. The key-wall apparently was placed by deposition through water that inevitably entered the forms because of the high permeability of the formations on which the key-wall was placed.*

Above the water level, a common soil-cement placement method was used in which a layer of contaminated soil was spread and bags of cement were placed at designated intervals and punctured. The cement was blended into the soil with a disc and the layer was compacted. Using this procedure a dome-shaped mound was formed over the crater. Radioactive debris (i.e., metallic debris, contaminated concrete, and other large pieces of material) too large to pass through the tremie pipe later was placed in an area, (called the "donut hole") reserved for it in the center of the structure and was "choked" in place with slurry.

Before the filling of the crater was completed, construction of the concrete cap or dome was started. It consists of 358 panels in 11 rings, and the panels vary in size from 20 by 21 feet at the outside to 6 by 7.5 feet near the center. The panels were made in place in forms and rested on polyethylene sheet. The design thickness of the panels was 18 inches, but the actual thicknesses ranged from 12.5 to 24 inches, with a mean of 17.3 inches (Ristvet 1980). The outer ring

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*Segregation, however, was observed in the core samples only at the bottom of the key-wall.

was laid first, and each panel was keyed to the abutting panels to prevent differential displacement (Figure 6).

Contaminated debris remaining after the "donut hole" was filled was placed into two concrete "boxes" constructed for the purpose and attached to the landward side of the dome.

The material within the Cactus Crater, covered by the concrete cap, consists of about 105,000 cubic yards of contaminated soil enclosing some 6,000 cubic yards of miscellaneous debris. The dome has a shallow slope and has been used as a landing pad for helicopters. The thick concrete key-wall around the dome is protected on the ocean side from wave action by a riprap "mole"—a necessary precaution during the construction phase because during the three-year cleanup operation four major typhoons and tropical storms hit Enewetak Atoll causing extensive destruction. One typhoon required complete evacuation of the atoll.

3.10 References

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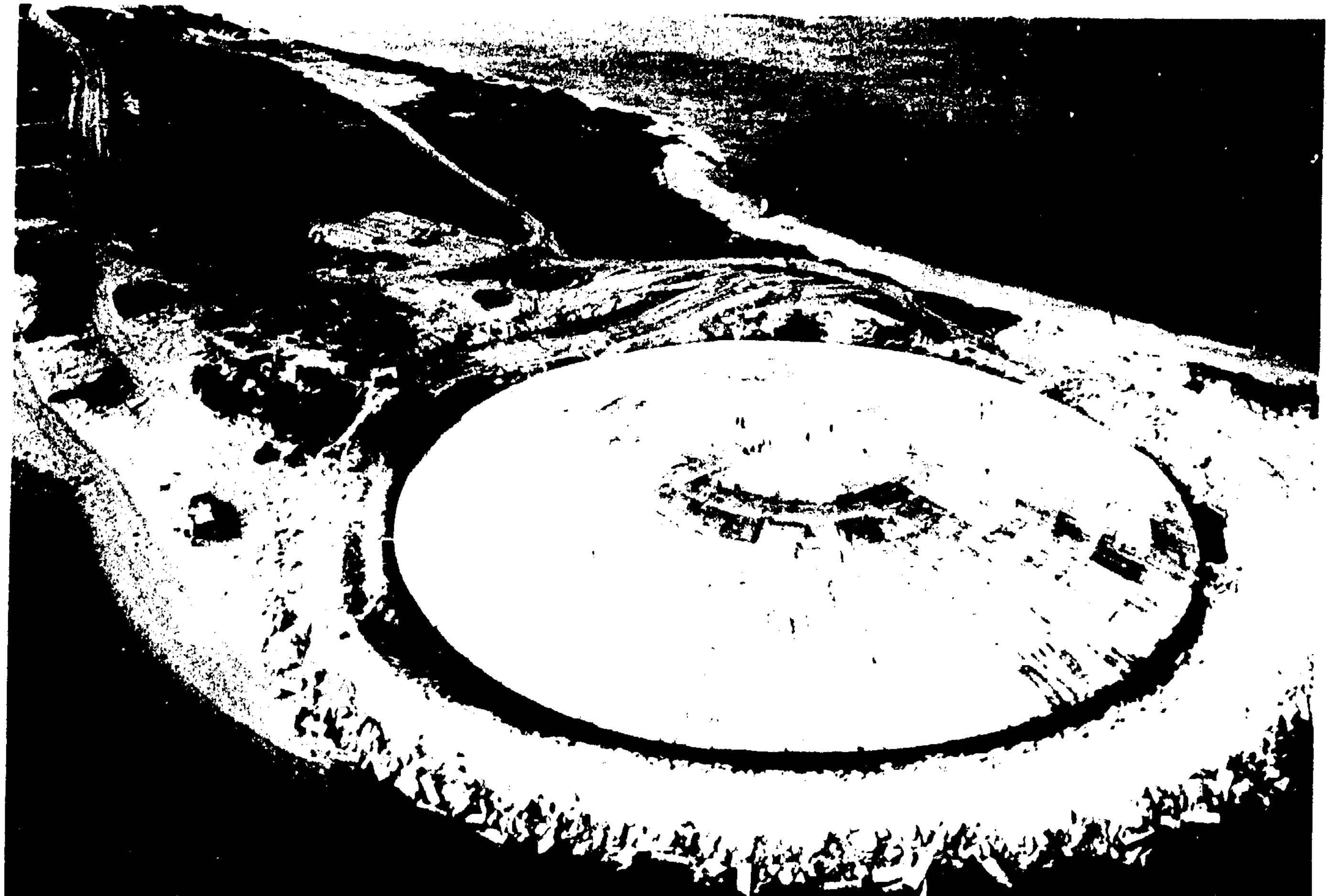

FIGURE 6 The containment structure at time of completion.
(Photo courtesy of Defense Nuclear Agency.)

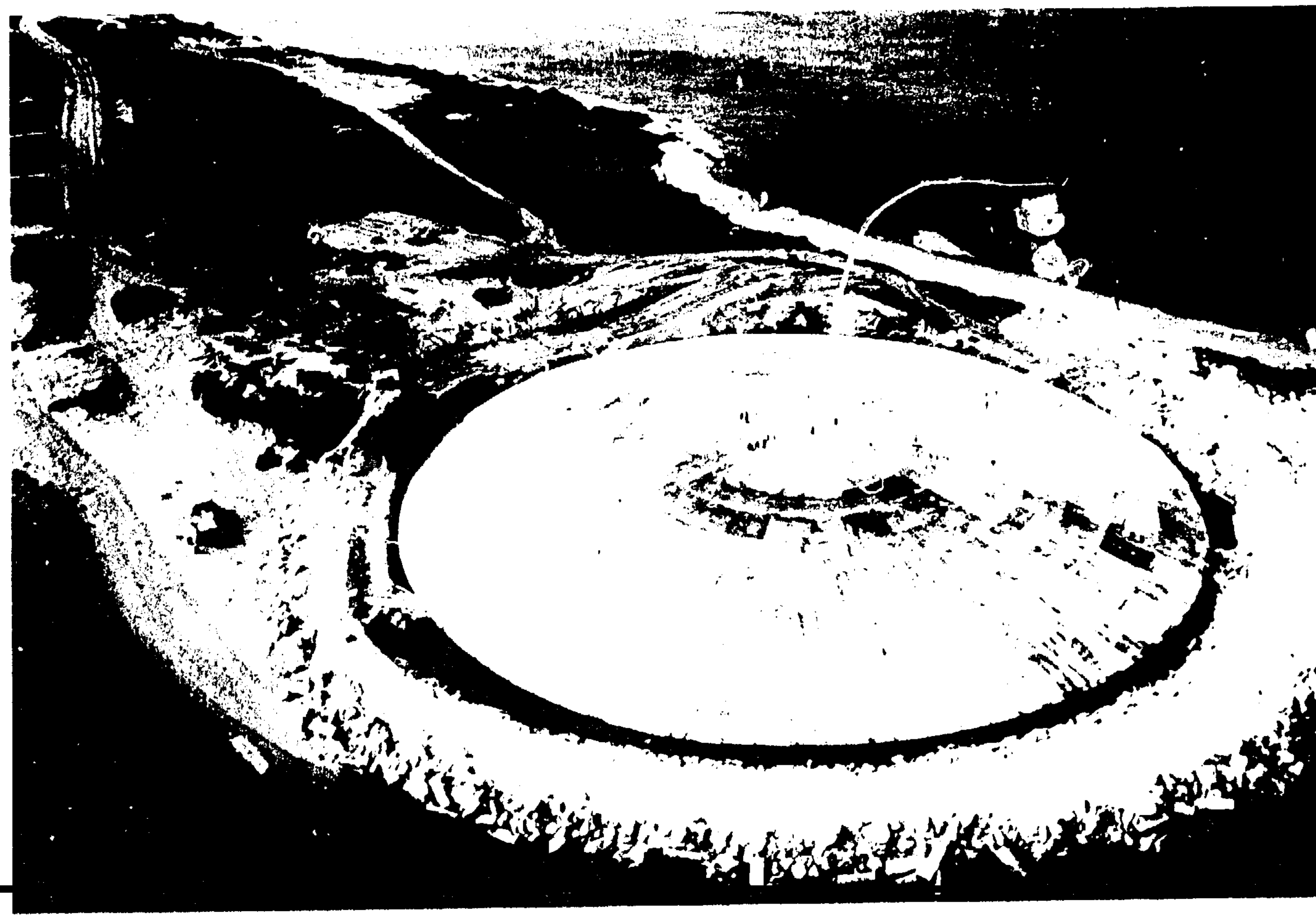

FIGURE 6 The containment structure at time of completion.
(Photo courtesy of Defense Nuclear Agency.)

Chapter 4
DESCRIPTION OF THE CONTAINMENT STRUCTURE

4.1 General Observations

The key-wall and concrete dome appear to be well finished and to consist of very good quality concrete. Some slightly open joints are visible between the slabs that form the dome, and a small number of very narrow cracks can be seen in a few of the slabs.

Field observations by the committee revealed that fine cracking extends through the midpoint of 6 of the 358 panels. Most of these cracks appear to have resulted from normal shrinkage of the concrete. The existing cracks may become larger, and similar cracks may develop in other panels.

The principal effect of this cracking is to reduce the effective size of the panel, functioning as riprap, to approximately 15 tons each half. Neither moisture movement nor future possible fissure to the underlying membrane is an issue with respect to durability of the dome.

4.2 The Drilling Program

At the outset of the study, it was recognized that information concerning the quality of the concrete, the effectiveness of construction of the dome, and the condition of the material within the structure could be obtained only by means of a drilling program. The Test Directorate, Field Command, DNA, agreed to undertake the drilling program for the committee. The report on the results of the drilling (Ristvet 1980) is a comprehensive document that includes historical, geological, and seismic data.

The drilling started on March 11 and ended on March 28, 1980, and much of it took place while committee members were on the site (March 21-28). Selection of the positions of many of the drill holes was made in cooperation with the committee, whose members were able to witness the drilling and recovery of cores and to examine the cores as they were extracted. Detailed descriptions of the cores are supplied by Ristvet (1980) but a general summary will be given here.

Twelve sections of the concrete cap were cored with a 4-inch diamond bit. Thicknesses varied from 12.5 inches to 24 inches with a mean of 17.3 $\pm$ 3.1 inches. The concrete was of high quality with some minor voids or air bubbles. One cap section showed a 1- to 2-inch honeycombed zone with interconnections of voids. All concrete cores from the dome were shipped to the Portland Cement Association for testing. These tests showed that the compressive strengths of all the cores were high and that the cores exhibited no properties that would lead to premature deterioration.

Four key-wall sections were cored, with the hole penetrating approximately 8 feet below the bottom of the key-wall. Three showed good quality concrete, but the lower half of one was friable, poor quality concrete. The latter key-wall section rested on highly fractured, moderately to well cemented beachrock. The other three rested on uncemented medium to fine sand. In one, the concrete was separated from the sand by a 1-foot layer of dark brown bentonite or attapulgite with low shear strength.

The overall conclusion is that the key-wall sections are of good quality concrete with some segregation of cement and aggregate at the bottom. They rest on a fractured coral or sand foundation. An interesting observation made during the key-wall drilling was that the water level in the drill holes appeared to be nearly synchronous with the tide, which suggests that water flows freely between the contents of the crater and the ocean.

As noted, the concrete dome consists of 11 rings of panels. Three holes were drilled and sampled through the third ring from the top. It was expected that after penetrating the cap, the drill would encounter soil-cement concrete, then tremie concrete, then crater fall-back, and, finally, the coral beneath the true crater bottom. None of the holes actually entered the undisturbed coral, but all penetrated into the fall-back zone.

In the first hole the material immediately under the cap was uncemented medium to fine soil-cement mixture with a few gravel-sized chunks of hardened cement. This continued for 12.5 feet and was followed by 3.5 feet of "oversize material" consisting of algal cobbles, broken pieces of tree limbs and boards, wire, and rebar. At a depth of 17 feet a section of 6-inch layers of poorly to moderately cemented tremie concrete alternating with uncemented soil and oversize debris began. This material had a strong smell of ammonia and continued for 5 feet. The next 2 feet, which smelled of hydrogen sulfide, consisted of oversize debris and cobbles. This was followed by 1 foot of well cemented tremie. The succeeding 6.5 feet had alternating layers of poorly to moderately cemented tremie concrete and oversize cobbles, soil, rebar, and wood fragments. Under this was 6 inches of well cemented tremie covering an unrecovered 5-foot section in which cuttings showed soil, minor gravel-size tremie, and wood fragments. The remaining 15 feet of the core consisted of crater fall-back, mainly medium to fine grain coraline sand and minor fractured gravel.

In order to determine the relative permeability of the crater contents, percolation tests and pumping recovery tests were conducted in the boreholes. Details from these permeability tests are reported by Ristvet (1980) and only the results are summarized here. The percolation tests, which involved filling the boreholes with water to the level of the cap base and then observing the water drop with time, were conducted in the soil-cement layer. Although the results were somewhat variable from borehole to borehole and at different depths within a borehole, the rate of water level drop in the soil-cement generally was very low; in one test there was no water level drop after 12 hours.

The pumping recovery tests, which involved pumping the boreholes completely dry and then observing the rate of water level rise, were conducted in the tremie material. These tests showed a very rapid recovery in the water levels; in one case the water level rose 2 feet in 5 minutes. Furthermore, water levels within the tremie concrete corresponded very closely to sea level and lagged only about 1/2 hour behind outside tidal fluctuations.

Thus, it appears that although the permeability of the soil-cement mixture is quite low, the permeability of the tremie concrete is much higher. Furthermore, in the tremie region there was relatively free communication with the ocean, perhaps mainly along channels provided by the oversize debris.

The soil-cement mixture was a moist, dense material that crumbled in the hand and the tremie concrete, a dense, partially cemented material. The whole of the crater contents, however, was rather impermeable to water except where there was channeling.

In summary, the cores showed that there are zones of incompletely cemented tremie concrete. This segregation of the concrete most likely resulted because the tremie pipe was not always kept below the surface of the slurry, probably due to movements of the barge carrying the injection equipment or failure to use a plug when each pumping sequence was started. The soil-cement above the water level also did not achieve the concrete-like character that was anticipated, possibly because of bacterial effects of organic material which prevented proper hardening of the concrete at the level of cement content used. Nevertheless, we believe that the keywall and concrete dome are satisfactory for all likely situations that will occur.

4.3 Radioactive Contents

Samples taken from the cores and water samples from the holes were analyzed at the Lawrence Livermore Laboratory. Water samples also were taken from two monitoring wells sunk outside the dome area, on the lagoon side, in positions calculated to intersect water passing through the crater and into the lagoon. The wells were fitted with unscreened slotted polyvinylchloride pipe for use in future monitoring.

The results of these analyses have been given by Robison and Noshkin (1981). To summarize the data here, mean values have been calculated, omitting samples taken in the fall-back zone. Results are given in pCi/g and the range gives the high and low values for the set of samples. Strontium and Pu were analyzed using wet chemistry methods and the others, using gamma ray spectrometry.

Radionuclide	Mean Concentration	Range
$^{239+240}Pu$	18.6	46 - 1.6
^{241}Am	2.8	6.3 - 0.20
^{90}Sr	20.6	52 - 5.5
^{137}Cs	8.7	27 - 0.24

As is to be expected from the nature of the cleanup and emplacement, there is a wide range of concentrations. Summing the ^{241}Am with the $^{239+240}Pu$, one arrives at a mean value for the transuranics of 21.4 pCi/g. If there are 12.6 Ci of transuranics in the dome (U.S. Department of Energy 1979) contained in 105,000 cubic yards of soil and one assumes a density of 1.8 g/cc for the soil, the average concentration to be expected would be:

$$\frac{12.6 \cdot 10^{12}}{105{,}000 \cdot 0.76 \cdot 10^{6} \cdot 1.8} = 87 \text{ pCi/g.}$$

The observed and calculated values are in reasonable agreement since the contribution from the material encased in concrete in the "donut hole" at the center of the dome is not considered and neither the means calculated from the samples nor the estimates made during the cleanup are likely to be very accurate.

Water samples taken from two different levels of a hole drilled in the dome also were analyzed. The water was filtered through a 0.45-micron filter and both filtrate and filter were analyzed. The mean values (in pCi/ℓ) were as follows:

Radionuclide	Soluble	Particulate
$^{239+240}Pu$	0.05	77.8
^{241}Am	0.005	67
^{90}Sr	331	112
^{137}Cs	248	146

The transuranics are essentially all associated with the particulate fraction and not as available for transport as ^{137}Cs and ^{90}Sr where the greater concentrations are in the soluble fraction. The mean values (in pCi/ℓ) for samples from the 20-foot level in the two wells outside the dome were as follows:

Radionuclide	Soluble	Particulate
$^{239+240}Pu$	0.142	164
^{241}Am	0.003	59
^{90}Sr	225	156
^{137}Cs	27	97

Somewhat higher concentrations of all nuclides were found in samples from the 40-foot level in one well. However, at the present time it is not clear if these radionuclides in the well samples are coming from the dome or from the fall-back zone or were present in the soil from other causes such as the work done in preparation for construction of the dome. An artificial beach was constructed for the off loading of the material placed in the dome and it is probable that contaminated soil was used in its construction.

In general, concentrations of radionuclides in all samples taken from the dome are low and are comparable to soil and sediment concentrations in the northern part of the atoll. The liquid samples have concentrations well below maximum permissible concentrations for the general public for drinking water.

4.4 References

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Chapter 5
HAZARDS ASSOCIATED WITH THE DOME

5.1 Function of the Dome

The function of the dome is to prevent people from being exposed to harmful amounts of radioactivity from the debris buried within. In practical terms, the dome will perform this function if it prevents people from having direct physical access to the contents and if any radionuclides exchanged between the contents and the environment do not create an unacceptable hazard.* Before addressing how well the dome can be expected to fulfill these goals, certain background material will be reviewed (sections 5.2-5.5).

5.2 Radionuclides in the Dome

The total amount of transuranics contained within the dome is estimated to be 12.6 Ci (U.S. Department of Energy 1979). Measurements of the fission product content are not available, but a crude estimate of a maximum of 50 Ci of ^{90}Sr and ^{137}Cs may be made using Atomic Energy Commission (1973) survey data. The average transuranic content of the material within the dome can be calculated to be about 87 pCi/g, about twice the permissible soil content of 40 pCi/g for islands designated for residential use. The average value measured from the drilling samples from the dome was 21 pCi/g, but this does not take account of contaminated debris that was encased in concrete in the center "donut hole" of the dome. Similarly, the average total value of ^{90}Sr and ^{137}Cs from the drilling samples was 29.3 pCi/g.

In addition, an estimated 380 Ci of activation and fission products plus an unknown amount of transuranics are contained in the fall-back debris in the true crater bottom and in the water beneath the material in the dome (Air Force Weapons Laboratory TR-77-242 1978). Prior to

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*Direct radiation from the contents is not of concern. Radiation from the fission products cannot penetrate the dome cap and have half-lives of less than 30 years. External exposures from transuranics are not significant because the principle emissions are alpha particles; the external dose from the ^{241}Am gamma radiation is negligible for the concentrations present in the dome.

the filling of Cactus Crater, the concentration of $^{239+240}$Pu in the fresh water within the crater was 0.116 ± 0.062 pCi/ℓ; the crater sediments had a concentration of 82 ± 2 pCi/g (dry weight) (Noshkin 1980, Table 4). These values are higher than the concentrations measured from within the containment structure (see section 4.3).

5.3 <u>Transuranics in the Surrounding Environment</u>

Radionuclides in the groundwater at Runit were measured in 1975, prior to the cleanup, by Noshkin and co-workers (1976). These measurements showed that plutonium had penetrated the groundwater to the deepest depths measured (73 m). Dissolved $^{239+240}$Pu ranged in value from 0.01 to 0.66 pCi/ℓ and in many of the wells was found to increase with depth. Two of the wells measured in 1975 are between Cactus Crater and the lagoon and are very near the two wells discussed in section 4.3. Measured values of dissolved $^{239+241}$Pu are similar in the two cases (between 0.08 and 0.17 pCi/ℓ) and both show a higher concentration in the well closer to the lagoon.

The largest quantities of transuranics at Enewetak are in the lagoon sediments. The entire distribution of the transuranics in the benthic environment at Enewetak has recently been reviewed by Noshkin (1980, Table 1). He estimates that the top 16 cm of the sediments has an inventory of 1185 Ci of $^{239+240}$Pu, 167 Ci of ^{238}Pu, 2190 of ^{241}Pu, and 475 Ci of ^{241}Am. These are distributed nonuniformly with the highest surface concentrations near the location of test sites. The highest concentrations are in the northwest area of the lagoon where surface activities of $^{239+240}$Pu are some four times higher than off Runit were surface activities range from 2 to 170 pCi/g (dry weight). The vertical distribution of the transuranics within the sediment column is highly variable from place to place (sometimes increasing with depth) and cannot be generalized easily.

Transuranics within the water column of the lagoon show a complex distribution, the spatial patterns being different for surface and bottom concentrations of $^{239+240}$Pu as well as for dissolved and suspended components. In 1974 the soluble $^{239+240}$Pu ranged in concentration from 0.002 to 0.075 pCi/ℓ. The total inventory in the water column of the lagoon in 1974 was 1.5 Ci in solution and 0.7 Ci associated with particulate material. Thus, the average quantity of plutonium in the water column is a small fraction of the sediment inventory.

The investigations of Noshkin and co-workers have shown that at both Enewetak and Bikini from 75 to 94 percent of the soluble $^{239+240}$Pu in the lagoon water is in the oxidized state (+5 or +6) with the remainder being in the reduced state (+3 or +4). All the plutonium associated with the particulate material is in the reduced state. Noshkin (1980) believes that most of the plutonium associated with the lagoon particulates is from resuspended sediments and is not transported out of the lagoon. On the other hand, the dissolved plutonium passes readily through dialysis membranes and seems to move without interaction with the sediment (Noshkin 1980).

The water in the lagoon is exchanged with the ocean approximately twice a year. Thus, about 3 Ci of dissolved $^{239+240}$Pu are removed from the atoll each year and an equivalent quantity remobilized from the sediments and other sources on the atoll. Noshkin has shown that the average concentration in solution in the water column can be accounted for by using a simple equilibrium model in which remobilization involves the sediment in the top 2.5 cm (Noshkin 1980).

5.4 Comparisons with Other Locations

It is useful to compare the situation at Enewetak with other locations where plutonium has been released to the marine environment. One of the most studied locations is at Windscale in the United Kingdom where authorized radioactive discharges are made to the Irish Sea from a nuclear fuel reprocessing plant. Since 1972 discharges of plutonium isotopes to the coastal waters have averaged about 100 Ci per month (ten times that in the dome). Since the first operations of the plant about 10,000 Ci of $^{239+240}$Pu have been discharged, 9,000 of which reside in the bed of the Irish Sea east of the Isle of Man (Hetherington et al. 1975, Penreath et al. 1979).

Measurements have shown that the discharged plutonium is rapidly removed to the sediments and that only a few percent of the inventory (as at Enewetak) remains in the water column. Within 10 km of the source, concentrations in the water column average about 0.7 pCi/ℓ and concentrations in the sediments average about 40 pCi/g (dry) with values as high as 105 pCi/g (dry) (Hetherington et al. 1975). These average concentrations exceed those at Enewetak, which are about 0.017 pCi/ℓ for lagoon water and 5.2 pCi/g for lagoon sediments (Noshkin et al. 1980).

Low levels of plutonium are discharged into Bombay harbor from a nuclear facility at Trombay. Here plutonium concentrations in the vicinity of the discharge point range from 0.004 to 0.02 pCi/ℓ in seawater and from 0.4 to 29 pCi/g in the suspended silt (Pillai et al. 1975, Pillai and Mathew 1976). A reprocessing plant at Tokai, Japan, discharges into the ocean where activity levels of $^{239+240}$Pu as high as 0.017 pCi/ℓ have been reported offshore (Kurabayashi et al. 1979).

Thus, authorized releases in different parts of the world have produced concentrations of transuranics in the marine environment comparable to or in excess of those found at Enewetak.

5.5 Transuranics in Marine Foods

Transuranics can be detected in marine organisms worldwide, in both salt and fresh water, due to global fallout from bomb tests. As would be expected, relatively high concentrations in marine organisms are found where there have been releases of transuranics (e.g., near Enewetak, Bikini, Windscale, Bombay, or Tokai).

Concentration factors in fish (i.e., the ratio of activity in a gram of fish to that in a gram of seawater from the same environment) vary considerably between species and between samples of the same species taken from different locations. Among fish there is little evidence of any strong or consistent relation to trophic level. These issues, as well as the results of measurements taken on 4,200 fish from 14 atolls in the Marshalls, were summarized recently by Noshkin and co-workers (Noshkin et al. 1980). They found concentration factors at Bikini and Enewetak to be similar, ranging from 5 to 10 in the muscle tissue of fish at all trophic levels (2nd to 5th). Mean concentrations at Enewetak in the muscle tissue of mullet and surgeonfish (which are primary consumers) were found to be 0.57 ± 0.61 and 0.15 ± 0.16 pCi/kg (wet), respectively. (Considerably higher values are measured in the stomach contents, the viscera, and the liver.)

In order to put such concentrations into perspective it should be noted that a daily consumption of as much as 1 kg of fish could exceed the current International Commission on Radiological Protection (ICRP) recommended limit for plutonium ingestion only if the fish had a plutonium concentration of 10,000 pCi/kg (Penreath 1980).

Robison and co-workers (1980) have made a detailed study of the potential radiological doses for Enewetak residents. Their estimates for the potential doses from marine foods are based on Noshkin's work, discussed earlier, and on a diet survey conducted when the Enewetak people were on Ujelang. They estimate that the mean daily intake of transuranics from seafood for an adult female will be 0.50 pCi of $^{239+240}$Pu and 0.12 pCi ^{241}Am. According to their dose assessment model, this results in an estimated bone marrow dose of 0.26 mrem/year, which is approximately 1 percent of the annual dose from the cosmic radiation in the Marshall Islands.

5.6 Dome Breachment

A number of possible failure modes might result in breaching of the dome including storm wave and typhoon activity, foundation settling, long-term weathering, shrinkage cracking, earthquakes and tsunamis, volcanic activity, generation of methane gas from the organic debris, and human-related activities such as vandalism. Each of these failure modes was considered, but only the first two, storm wave and typhoon activity and foundation settling appear plausible to the committee.

Probably the greatest hazard to the dome structure as well as to the people living on Enewetak Atoll will come from typhoons, which sometimes completely inundate these low islands. Although the dome was designed to withstand severe storm wave and typhoon activity, the typhoons in this part of the world are so severe that a series of them conceivably could cause breachment of the dome structure. The mole, which surrounds the dome on the north and northeast sides, serves as the first defense for waves from that direction. If the mole failed (and was not repaired), the next typhoon could attack the key-wall of the containment structure, probably causing scour on the reef side. This attack would be minimized because the heavier riprap in the mole in all likelihood would be deposited on or in front of the ring wall. The ring wall sections (12 feet by 2 feet by 3.5 to 5 feet) each weigh more than 6 tons, much heavier than are required to resist wave action, and would therefore function as large riprap. Should the ring wall be washed out, a most unlikely event, wave energy would be absorbed by wave run-up on the dome, which would act like a beach in absorbing wave energy. However, the dome panels, each weighing more than 30 tons, also would act as riprap highly unlikely to be moved by wave action.

It was mentioned in section 3.8 that Cactus Crater might have been partly formed in a man-made extension to Runit Island, and, if so, the containment structure could be vulnerable to erosion on the lagoon side should the beach ever retreat to the edge of the dome. However, on the basis of a recent study of aerial photographs of Runit, Ristvet believes that the 1981 shoreline, which is about 75 feet from the edge of the dome, may be near "equilibrium" since it is close to the maximum extension of the near subsurface beachrock (Byron Ristvet, letter to the committee, November 1981).

The committee believes that the probability of dome breachment due to storm wave and typhoon activity is quite low. However, to facilitate early detection of typhoon-induced effects it recommends that visual inspection of the dome structure, the surrounding mole, and the beach on the lagoon side be performed at regular intervals (as a minimum, after each major typhoon).

Some settling with time in response to loading is conceivable. Furthermore, vegetation such as tree limbs included within the debris can be expected to undergo bacteriological reduction, resulting in slight amounts of settlement within the dome. Such settlement, however, would not impair the function of the dome cap in denying human access to the contained material. Resistance against movement of the dome cap in response to settlement of the contents of the dome is provided by the key-wall. Although the key-wall may spread outward slightly in response to stresses produced by settlement, the concrete cap functions simply as a series of cover slabs, not a true dome structure, and can easily bridge over any localized areas of differential settlement or settle without any impairment of the dome's performance.

5.7 <u>Hazards Associated with Leaching from the Containment Structure</u>

The results of the drilling program described in chapter 4 show that the tremie and the soil-cement operations were not fully successful. Within the tremie region there are zones of oversized debris and unconsolidated tremie material that provide channels for water movement. The rapid tidal response in the boreholes indicates that the water in the structure is closely coupled to the island's groundwater. Therefore, at least part of the radioactivity contained in the structure is available for transport to the groundwater and, subsequently, to the lagoon, and it is important to determine whether this pathway may be a significant one.

It is not clear whether Cactus Crater (and its vicinity) is a greater or lesser source of transuranic movement to the lagoon than it was before the cleanup. Before Cactus Crater was filled it was one of the sources of transuranics being remobilized to the waters of the lagoon. Noshkin estimates that about 0.4 percent of the dissolved plutonium present in the lagoon originated from the material at the bottom of the crater (V.E. Noshkin, personal communication to R.W. Morse, October 23, 1981). Several conditions, however, were changed by the cleanup operations: the fresh water run-off to the water table was changed by the construction of the dome; the cleanup of soil on the island has reduced movement of transuranics to the groundwater; and the filling of the crater has modified the amount of transuranics being transported from the crater.

It is possible to demonstrate that leaching from the dome does not create a significant new hazard by use of simple inventory arguments without having to speculate about possible remobilization processes taking place within the structure. It was indicated in section 5.3 that there is about 1.5 Ci of plutonium continuously in solution in the lagoon and that 3.0 Ci are lost to the ocean annually. The amount of plutonium in the containment structure simply is not sufficient to sustain any significant increase in the level of activity in the waters of the lagoon. To take an extreme example, if as much as 1 Ci/yr of plutonium were being remobilized to the lagoon now, the average concentration in the lagoon would increase only by 33 percent and the effective half-life of the plutonium in the structure would be about 8 years. Since the levels of plutonium in the waters of the lagoon would have to be increased by several orders of magnitude to exceed international standards for drinking water, leaching from the dome is not likely to create a hazard.

An upper limit for the radiation dose caused by leaching from the dome can be estimated by simply assuming that all of the transuranics are rapidly remobilized to the waters of the lagoon (i.e., in a time less than 30 years so that all effects would occur within one generation). As already noted, about 3 Ci of plutonium need to be remobilized annually to maintain the present concentration in the water column, and the estimated dose rate to bone marrow (for all transuranics) from the ingestion of marine foods is 0.26 mrem/yr (section 5.5). If the concentrations of transuranics in marine organisms are proportional to the concentrations in the water column (which is the assumption behind the use of the usual "concentration factor"), then the total additional dose from the remobilization of 12.6 Ci to the lagoon's water column should be approximately 4.2 times (12.6 divided by 3) the estimated annual dose due to the present concentration, or 1.1 mrem. In other words, the dome at most could sustain the present levels for about 4.2 years.

This upper limit of 1.1 mrem for the total dose due to remobilization of the dome's transuranics to the waters of the lagoon is independent of the exact mechanisms by which it might occur. A dose of 1.1 mrem to bone marrow also is small compared to doses that can be expected from other causes at Enewetak. For example, cosmic rays in the Marshall's produce a dose to bone marrow of 1.1 mrem every <u>two weeks</u>. Thus, even a relatively rapid remobilization of all the transuranics contained in the dome to the waters of the lagoon would not be expected to create a significant new radiological hazard.

A simple model can be constructed to estimate the increased 30-year dose to bone marrow through the marine food chain if leaching from the dome to the lagoon took place with an effective half-life of T (see appendix A). If all 12.6 Ci in the dome were available for leaching and eventually went into solution in the lagoon (certainly an overly conservative assumption), the estimated increased dose as a function of the effective half-life in the dome would be:

Effective half-life in dome (years)	Extra 30-year dose to bone marrow (mrem)
10	0.95
20	0.71
50	0.37
100	0.20
200	0.12
400	0.05
1000	0.02

5.8 <u>Hazards Associated with Breaching of the Containment Structure</u>

As discussed above, radioactive material can escape from the containment structure either by leaching, in which case all the radioactivity would be waterborne, or by actual breaching of the dome structure, in which case the radioactivity would be both waterborne and airborne. If part of the dome were torn away, transport of the radioactive material, now aggregated for the most part into larger particles by the cementing process, most likely would occur during heavy storms, and the most credible result would be that the wet and heavy contents would be swept into the lagoon. The whole area would be drenched and, hence, any material that had become airborne would be washed out rapidly. It is noteworthy that throughout the cleanup effort field workers wore air filters for protection against airborne plutonium. Radioactivity on all but a handful of filters was too low to be detected in totally dry conditions. Thus, even during the most adverse possible conditions (i.e., during the scraping, transporting, and dumping of the contaminated soil), the amount of airborne plutonium was negligible.

Estimates of the potential future radiological dose at Enewetak due to atmospheric resuspension of transuranics have been made by Robison and co-workers (1980) based on resuspension experiments conducted at Enewetak and Bikini. These measurements included both the contributions of sea spray and suspended aerosols of terrestrial origin (the "normal or background" mass loading at both locations was approximately $55\mu g/m^3$ of which about 60 percent was due to sea salt); they also included high activity situations such as the cultivation of open fields.* Dose rates were calculated assuming 8 hours per day of high activity work. For surface soil transuranic concentrations equal to those at Enjebi (which averages approximately 20 pCi/g), the potential dose rate due to the inhalation pathway is estimated as 12 mrem/yr (Robison et al. 1980). This would certainly overestimate the dose rate to a visitor to Runit even if large quantities of unconsolidated material were to erode from the dome. Thus, if the "off limits" ban on the island were violated, potential health effects from such resuspension appear unimportant.

With respect to the future of the containment structure, the committee believes that the structure will maintain its physical integrity for a long period of time (probably in the range of 10^2 to 10^3 years). However, it is impossible to estimate this with any degree of certainty because the principal threat comes from the long-term cumulative effects of large storms. If the key-wall eventually were to be breached, the most likely outcome would be an erosion of unconsolidated material out of the dome to the lagoon and reef, with the dome subsiding upon the consolidated material. This would not

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*Based on measurements made near Windscale there is some evidence that plutonium may be concentrated in the sea surface and subsequently injected into the atmosphere by sea spray and transported by the wind (Cambray and Eakins 1980). Any such concentration effect, if it does exist, would be included in the measurements reported by Robison and co-workers.

result from any conceivable single event but would be the consequence of cumulative effects over a long period (plus, of course, the absence of any attempt to make repairs). It is the committee's view, however, that even if this eventually were to happen, the dome would continue to perform its intended functions. The collapsed dome probably still would prevent human access to the contaminated debris buried within. Any soil-cement or tremie material spilling or eroding from the dome into the lagoon would cause little change to the concentrations of transuranics there. Measurements on such material drilled from the dome showed a mean concentration of transuranics of 21.4 pCi/g with a range of 1.8 to 52.3 pCi/g. Lagoon surface sediment measurements taken within a mile of Cactus Crater show a range of transuranic concentrations of from 1.9 to 64 pCi/g (dry) with a mean of about 30 pCi/g (dry) (Atomic Energy Commission 1973). Thus, deposition of material from the dome on the lagoon floor would not necessarily increase the concentrations of transuranics in the superficial sediments.

Even if material from within the dome were to contribute to the water column concentrations independently of the radioactivity now in the sediments, the upper limit of the radiological hazard would be the same as that estimated in the previous section for leaching. Thus, if all of the transuranics in the dome were remobilized to the water column of the lagoon, the result at most would be an increased dose of only 1 mrem (to bone marrow) through the ingestion of marine foods.

5.9 Summary

It is clear that the estimates made here and in the previous section depend directly on the validity of the dose estimates calculated by Robison and co-workers. These, in turn, depend on diet surveys made at Ujelang and on measurements made by Noshkin and co-workers (1980) of the transuranic concentrations in marine foods. It is conceivable that new observations will lead to new estimates of the bone marrow dose from transuranics in marine foods. However, two points can be made to support the view that such changes are not likely to alter the basic conclusions of this report.

The assumption of the rapid remobilization of all the dome's transuranics is an extreme one and is not supported by any existing evidence. For example, if the rate of remobilization from the dome to the lagoon was similar to that from the lagoon's sediments, i.e., having an effective half-life of 400 years (Noshkin 1980), and only 20 percent of the dome's contents were available for remobilization, the 30-year integral dose to bone marrow would be only 0.01 mrem (see section 5.7). Further, the estimated dose from the ingestion of marine foods from present concentrations in the lagoon is small. It would require an increase of about 10^3 in the present estimate to produce a dose level that would be of serious concern.

In summary, the committee believes that it is highly unlikely that the containment structure will fail in its function of preventing human access to its contents and that no credible health hazard would result even if the containment structure's transuranics were leached or eroded into the lagoon.

5.10 References

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Chapter 6
OTHER ISSUES

6.1 Runit Island

Although Runit Island is to be off-limits forever, it is possible that the Enewetak people and others believe this prohibition to be related to the dome. This, however, is not the case, and the committee emphasizes that its conclusions regarding the safety of the containment structure should not be interpreted to mean that it believes there is no possible hazard on Runit.

The surface of Runit Island was cleaned up to below the "agricultural" level of 40 to 80 pCi/g of soil and the southern part of the island satisfied the residential criterion of less than 40 pCi/g (U.S. Department of Energy 1980). However, there were some 14 detonations on or near the northern part of Runit, two of which are thought to have distributed fragments of metallic plutonium on the island and in the lagoon. Thus, there is a hazard of uncertain magnitude on Runit from fragments of plutonium and plutonium dust in subsurface pockets where concentrations of several thousand picocuries per gram have been found. It is possible that undiscovered pockets contain particles of metallic plutonium that accidentally could be picked up and carried off the island. In addition, there was a great deal of earthmoving on Runit during the years of testing with buried plutonium being mixed up with general debris and so there are areas that could become exposed by action of rain, wind, and waves where concentrations are more than 160 pCi/g. It is estimated that, exclusive of the contents of the dome, there might be about 10 Ci of transuranics on Runit (i.e., nearly as much as there is sealed inside the dome) (Committee briefing by R. Ray, Deputy Director for Pacific Operations, Nevada Operations Office, U.S. Department of Energy, May 28, 1980). For these reasons the island has been quarantined since the cleanup operation.

Thus, it seems to the committee that although the hazard presented by the dome is negligible, the same cannot be said for Runit Island as a whole. On the other islands the transuranic contamination was very near the surface, consisted mainly of oxides with very low rates of movement through soil, and could be removed fairly easily by bulldozing.* On Runit there is plutonium well below the surface which would be difficult to remove without scraping off the soil down to bedrock. The seriousness of the quarantine has been made very clear to the people of Enewetak and they so far have respected it. The committee strongly endorses their determination to retain the quarantine of the entire island of Runit.

6.2 Enjebi Island

As explained in the Preface, the principal mission of the committee is to "assess the effectiveness of the Cactus Crater structure in preventing harmful amounts of radioactivity from becoming available for internal or external human exposure." In addition, the committee also was instructed that its assessment of the Cactus Crater structure was to be "set against an understanding of the expected living patterns of the people of Enewetak in terms of their degree of contact with Runit Island and their exposure otherwise to residual radioactivity on the atoll." Consequently, the committee believes it must comment on the radioactivity hazard on Enjebi since it probably is inevitable that the Dri-Enjebi will return to that island to live and grow at least some of their food.

6.2.1 Radioactivity on Enjebi

Because Enjebi was not at first expected to become a residential island, soil was removed from only about 17 percent of its surface. The soil removed contained about 5 Ci of transuranics. However, there are only localized areas (about 3 percent) that do not satisfy the transuranic habitation standard of 40 pCi/g soil (U.S. Department of Energy 1980). Thus, transuranics are not a problem on Enjebi.

The principal concern in the settlement of Enjebi must be directed toward the fission products, especially ^{90}Sr and ^{137}Cs. As mentioned earlier, these were not included in the DNA cleanup mission because they were leached out of the top several inches of topsoil and were concentrated at depths not feasible for excision. These fission products are particularly troublesome because they concentrate in food crops, especially coconuts, and, hence, are easily ingested.

6.2.2 Dose Assessments

An extensive dose assessment study utilizing data collected on Bikini and Enewetak Atolls over a period of many years has been carried

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*An exception may be Lujor, near Enjebi, where it has been stated (letter from W. J. Bair, Chairman, U.S. Department of Energy Enewetak Advisory Group, to H. Hollister, U.S. Department of Energy, Pacific Northwest Laboratories, Richland, Washington, April 28, 1978) that "the soil profile on Pearl [code name for Lujor] is anomalous since the concentration of transuranics appears to be uniform with depth." The final island certification survey after the cleanup, however, reports that Lujor meets the criterion for an agricultural island and that there are no known or suspected radiological burial sites.

out by Robison and co-workers (1980) at the Lawrence Livermore Laboratory. They estimate that the 30-year integral doses for living on Enjebi are 5.7 rems (whole body) and 6.1 rem (bone marrow) when imported foods are available and 10 rems and 11 rems, respectively, when imported foods are unavailable. For the southern half of the atoll (where the people now reside), the 30-year integral doses are 0.10 rem (whole body) and 0.12 rem (bone marrow) when imported foods are available and 0.20 rem and 0.26 rem when such foods are unavailable. Thus, the calculated doses for living on Enjebi are somewhat higher than the total of 5 rems that is the maximum allowable limit for a large population in the United States.

The nature of the hazards that would be faced by a return to Enjebi in the near future (i.e., before the fission products have been reduced further by decay) have been explained to the people of Enewetak, particularly by the dual-language document, The Enewetak Atoll Today (U.S. Department of Energy 1979). The decision about such a return can be made only by the Dri-Enjebi themselves after a realistic and informed comparison of the estimated radiation risks with the other risks to which they are exposed in their normal life.

6.3 References

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Appendix A

ESTIMATED 30-YEAR INTEGRAL DOSE VS RATE OF REMOBILIZATION FROM DOME

The total stock of transuranics present at any time in the lagoon due to leaching from the dome can be estimated by assuming that: the rate of remobilization is proportional to the quantity of transuranics remaining in the dome and the remobilized transuranics are removed by tidal flushing from the lagoon with a turnover time τ. This problem is mathematically analagous to a two-stage radioactive decay process in which the increased standing stock in the lagoon is analagous to the amount of the intermediate nuclide present. If remobilization takes place with an effective half-life T, then the increased standing stock ΔS is given by:

$$\Delta S = \frac{\tau\lambda C_0}{1-\tau\lambda}\left[e^{-\lambda t} - e^{-t/\tau}\right]$$

where $\lambda = 0.693/T$.

If it is assumed that the dose rate from marine foods is proportional to the standing stock of transuranics in the lagoon (this effectively is the usual "concentration factor" assumption), then the extra 30-year dose from ΔS can be written as:

$$\Delta D_{30} = \frac{D_0}{S_0}\int_0^{30} (\Delta S)\,dt$$

or

$$\Delta D_{30} = \frac{\tau D_0 C_0}{S_0}\left[(1-e^{-30\lambda}) - \tau\lambda(1-e^{-30/\tau})\right]$$

where D_o is the dose rate due to the present standing stock S_o. If the turn-over time of the lagoon (τ) is short compared to T, then:

$$\Delta D30 = \frac{\tau D_o C_o}{S_o} \left(1 - e^{-0.693\left(\frac{30}{T}\right)}\right)$$

Assuming, as described in chapter 5, that D_o = 0.26 mrem/yr, τ = 0.5 years, S_o = 1.5 Ci and assuming further that all of the 12.6 Ci in the dome is available for leaching, then the extra 30-year dose as a function of effective half-life in the dome is:

$$\Delta D = 1.1 \left(1 - e^{-0.693\left(\frac{30}{T}\right)}\right) \text{ mrem}$$

The data in section 5.7 are calculated from this expression.

Appendix B
BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

ROBERT W. MORSE is a senior scientist with the Woods Hole Oceanographic Institution. He received his B.S. in 1943 from Bowdoin College and his M.S. in 1947 and Ph.D. in 1949 from Brown University. He served on the Brown University faculty from 1946 to 1964 as professor of physics, chairman of the department, and dean of the college. Between 1964 and 1966, he was assistant secretary of the Navy for research and development. He later served as President of Case Western Reserve University and as Director of Research at Woods Hole Oceanographic Institution. He has served as chairman of numerous committees, including the National Academy of Sciences committees on undersea warfare, energy management, human resources, and the ocean resources board.

JOHN P. GNAEDINGER specializes in structural and foundation engineering and soils mechanics. He is a founder, past president, and chairman of Soil Testing Services, Inc. He received his B.S. in civil engineering in 1945 from Cornell University and his M.S. in civil engineering in 1947 from the Northwestern University Technological Institute. During his career he has been responsible for the original design of soil testing equipment, many large-scale national and international soil investigations, and structural and foundation design projects. He is a former chairman of the Building Research Advisory Board of the National Academy of Sciences and has served as a member and as chairman of many of its committees.

STEPHEN M. KIM is President, RMC Technical Services, Radiation Management Corporation. He received his B.S. degree in 19[illegible]1 from Pan American University. He has done graduate work in nuclear chemistry at Penn State and in geochemistry at the University of Illinois; specializes in radiogeochromology dealing with ^{14}C and tritium and the movement of radionuclides in the environment. He is a member of the National Academy of Sciences Committee on Radioactive Waste Management Panel on Savannah River Waste.

COLIN A. MAWSON, prior to his retirement, was head of the environmental research branch of Atomic Energy of Canada, Ltd. He specialized in trace metal physiology, radioactive waste management, and environmental monitoring. He received his B.S. in 1929, M.S. in 1930, and Ph.D. (physiology) in 1933 from Manchester University (England). He is a member of the National Academy of Sciences Committee on Radioactive Waste Management.

WILLIAM F. MERRITT, prior to his retirement from the Chalk River Nuclear Laboratories of Atomic Energy of Canada Ltd., was in charge of underground radioactivity monitoring of hazardous waste management areas, including subsurface and surface water and soil. He worked for several years in radionuclide standardization and was head of the radiochemical analysis laboratory specializing in activation analysis for the environmental sampling programs (rainfall, snowfall, gas collection). He has a B.S. in chemistry and physics.

FRANK L. PETERSON is in the Department of Geology and Geophysics of the University of Hawaii. He received his B.A. in 1963 from Cornell University and his M.S. in 1965 and Ph.D. in 1967 from Stanford University. He specializes in groundwater geology including fluid flow and groundwater stoop in coastal and insular regions; Glyben-Herzberg lens dynamics; occurrence of and exploration for groundwater; land subsidence; and, a broad range of engineering geology problems.

JOHN H. WIGGINS, Jr., a registered civil engineer in the State of California, is president of the J. H. Wiggins Company. He received his B.S. in physical sciences in 1953 from Stanford University, his M.S. in geophysics in 1955 from St. Louis University, and a Ph.D. in civil engineering in 1961 from the University of Illinois. He specializes in risk and failure analysis and the study of technological side effects with regard to their impact on the social, legal, and economic areas and has written over 25 technical papers. He currently is a member of the Advisory Board on the Built Environment of the National Academy of Sciences.

ALFRED A. YEE, a registered structural engineer, was President of Alfred A. Yee and Associates and currently is head of Alfred A. Yee Division of Leo A. Daly Company. He received a B.S. in civil engineering in 1948 from Rose-Hulman Institute of Technology and his M.S. in 1949 from Yale University. He specializes in all aspects of design and construction, including housing, office buildings, laboratories, pier and wharf structures, towers, tanks, and theaters; he pioneered the art of composite construction work with prestressed precast concrete units and developed his design concept involving redistribution of moments and plastic hinges. He was elected to the National Academy of Engineering in 197[illegible].